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ABSTRACT

Comet C/2013 A1 will make a very close approach with the planet Mars on 2014 October 19. For this event, we compute the density of cometary dust particles around the *Mars Express* spacecraft, in order to assess the real risk for space probes. We also estimate the zenithal hourly rate (*ZHR*) and discuss observational opportunities for the resulting Martian meteor shower. We find, for a surface of 2.7 m^2, that the *Mars Express* spacecraft will experience approximately 10 impacts from particles larger than 100 μm in size. The fluence per square metre is found to be 3.5 during the encounter. The equivalent *ZHR* is computed to be $ZHR \simeq 4.75 \times 10^9\ h^{-1}$, making this event the strongest meteor storm ever predicted. We call this event a 'meteor hurricane', which we define to be a meteor shower with *ZHR* exceeding $10^6\ h^{-1}$. The event will last approximately 5 h in total, and peak around 20:00 UT (Earth UT time). We call for observations of this unique event by all possible means, but also warn operators of Mars-orbiting spacecraft against the risks of impacts from comet particles larger than 100 μm, with impacts speeds of 57.42 km s^{-1}.

Key words: meteorites, meteors, meteoroids – planets and satellites: individual: Mars.

1 INTRODUCTION

Soon after its discovery on 2013 January 3 (McNaught, Sato & Williams 2013), it was recognized that the long-period comet C/2013 A1 (Siding Springs) will pass very close to Mars as it enters the inner Solar system. Although a collision of the comet with Mars has been ruled out, there is still a potential for the comet debris to impact the planet. The closest approach between the comet and Mars is expected to occur on 2014 October 19 at 18: 17 ± 00: 12 TDB, with a minimum approach distance of $1.51 \times 10^5 \pm 5.20 \times 10^4$ km, according to our calculations (see also Section 2).

The ejected particles will form a tail that we expect to cause a huge meteor storm at Mars. This represents a significant hazard for man-made infrastructure in orbit around Mars or on the Martian surface. Four satellites are expected to be present at Mars on this date – NASA's *Mars Reconnaissance Orbiter* and *Mars Odyssey* and (en route) *MAVEN*; ESA's *Mars Express*; and ISRO's (en route) *Mars Orbiter Mission* (MOM) – as well as the rovers Mars Exploration Opportunity and Mars Science Laboratory Curiosity.

Moorhead et al. (2014) have already computed the spatial density of dust particles as the comet passes Mars, in order to assess the real impact risks for spacecraft orbiting the planet. In this paper, our aim is exactly the same, but the method is different. We first use a simple method to estimate the spatial density of the dust at Mars, before utilizing the detailed model of Vaubaillon, Colas & Jorda (2005a) that takes into account recent photometry measurement of the comet. The latter model has previously been used to compute the dust environments of comets 9P/Tempel 1 and 67P/Churyumov–Gerasimenko (Vaubaillon, Lamy & Jorda 2004).

The paper is organized as follows: Section 2 presents the orbit determination of the comet and the fit of the [*Afρ*] curves used to derive the number of real particles the comet ejects. In Section 3, we describe the method and results using the simple Interplanetary Meteoroid Environment for Exploration (IMEX) to calculate the fluence of particles at Mars and *Mars Express*. In Sections 4 and 5, we describe the method of Vaubaillon et al. (2005a) and use this to calculate the fluence of particles at Mars and at the spacecraft. Finally, in Section 6, we present conclusions on the risk of impact to spacecraft at Mars, the particle fluences and the observation opportunity presented by the resulting Martian meteor shower.

2 COMET C/2013 A1 SIDING SPRING ORBIT AND [*AFρ*] CURVES

2.1 Orbit determination

We determine the orbit of the comet using astronomical observations and a dynamical model based on Maquet et al. (2012).

The dynamical model includes gravitational perturbations of all the planets of the Solar system, using the planetary ephemeris INPOP10a (Fienga et al. 2011), as well as the relativistic effects

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of the Sun. We do not include non-gravitational forces, because it is impossible to determine the amplitude of the non-gravitational forces, at the time this paper is written. As the comet is still more than 3 au from the Sun, non-gravitational forces due to outgassing do not yet have a significant effect on the orbit of the comet. In addition, because C/2013 A1 is a long-period comet, which is presumably on its first and last passage close to the Sun, there is no information available from earlier apparitions of the comet.

Astrometric measurements taken from the IAU Minor Planet Center are used for the data fit. This data set consists of 297 observations from 2012 October 4 to 2013 September 10, and includes pre-discovery observations from the PANSTARRS 1 and Catalina surveys. The O − C rms we obtain is 0.42 arcsec. Note that the data the furthest from the fitted orbit ($>3\sigma$) are given a lower statistical weight than the other ones. The difference of the minimum distance at closest approach is less than 9000 km between our solution and that provided by JPL HORIZONS. This is due to the way the data set is chosen and the weights are computed.

The orbit of the comet is hyperbolic ($e = 1.0005 \pm 0.0002$) and retrograde ($i = 129.044 \pm 0.001$). The perihelion occurs 6 d after the close encounter with Mars on 2014 October 25, at a distance of 1.4 au from the Sun.

2.2 [*Afρ*] curves fit

Aperture photometry requires counting the number of photons that reach us from the comet, through several diaphragms. Here, we use these measurements to derive the [*Afρ*] parameter that was introduced by Ahearn et al. (1984) as a way of comparing results from observations that used different aperture sizes. [*Afρ*] is related to the number of dust particles ejected from the cometary nucleus, and it is the product of the albedo *A* of grains, the fill factor *f* and the field radius ρ of the diaphragm.

Following Vaubaillon et al. (2005a), we suppose $[Af\rho](r_h)$ varies with the heliocentric distance r_h as

$$[Af\rho](r_h) = [Af\rho]_0 \left(\frac{r_0}{r_h}\right)^{\gamma}, \quad (1)$$

where $[Af\rho]_0$ is a reference [*Afρ*] for the given heliocentric distance r_0 and γ is a constant. The parameters we need to determine are $[Af\rho]_0$, r_0 and γ.

We use observations from Cometas_obs.[1] However, according to Fig. 1 there is a dispersion of the measurements around a heliocentric distance of 7 au. We therefore fit three solutions to the data, using least-squares fitting. The upper dotted curve (hereafter called the ‘high solution’), requires the largest value of [*Afρ*]. The lower dot–dashed curve (hereafter called the ‘low solution’), requires the smallest value, while the intermediate continuous curve (hereafter called the ‘nominal solution’), is derived using all the data. This latter solution corresponds to the most meaningful range of physical parameters.

The three solutions with [*Afρ*] in cm and r_h in astronomical units are

$$Af\rho(r_h) = 1287.67 \left(\frac{1.40}{r_h}\right)^{0.16} \qquad \text{(dot)} \quad (2)$$

$$Af\rho(r_h) = 39185.02 \left(\frac{1.40}{r_h}\right)^{2.90} \qquad \text{(dot–dashed)} \quad (3)$$

[1] http://www.astrosurf.com/cometas-obs/

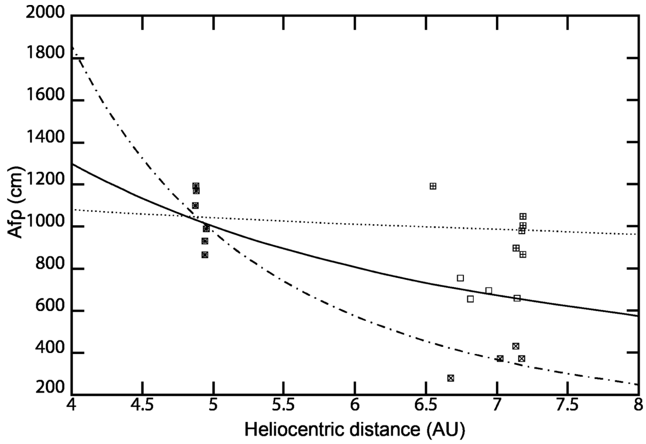

Figure 1. The three solutions of the [*Afρ*] fit.

$$Af\rho(r_h) = 4447.23 \left(\frac{1.40}{r_h}\right)^{1.17} \qquad \text{(line)}. \quad (4)$$

3 FIRST APPROACH: THE SIMPLE IMEX MODEL

A meteoroid model was developed in the context of the ESA-funded IMEX, the aim of which is to develop a model that can predict the hazard of meteoroid streams to interplanetary spacecraft (Soja et al., in preparation). This model is necessarily simple, as it was designed to assess the risk from streams of all observed short period comets that reach the inner Solar system (>400 are known). However, this model can provides a useful test model for individual cases. We therefore use this to give an initial estimate of the fluence of particles from comet C/2013 A1 on to *Mars Express*. A more detailed model is described in Section 4.

This simple model emits particles 224 particles at each of 100 emission points evenly spaced in true anomaly along the comet orbit between 7 au and perihelion. The comet orbit for this simple case is taken from an SPK file from the JPL HORIZONS system, because this model is designed to use this type of data directly. The position of *Mars Express* is taken from a NAIF (Navigation and Ancillary Information Facility) kernel provided by the NASA data base. Particles are emitted evenly with about 10° separation on the sunlit hemisphere of the comet. Particles have mass 1×10^{-9} kg (∼60 µm) and density 1000 kg m^{-3}, although calculated fluxes correspond to particles larger than 1×10^{-9} kg. Ejection velocities are derived from the model found in the cometary trails model of Kelley, Reach & Lien (2008) for 67P/Churuyumov–Gerasimenko, without the zenith angle dependence, and with an added dependence on comet radius. This model was found to provide the best fit between our model and observations of the 67P/Churuyumov–Gerasimenko trail (Soja et al., in preparation). Ejection velocities are a few m s^{-1}. Tests with an ejection velocity a factor of 3 higher, as found using the model of Whipple (1951), as adapted by Jones (1995) and Brown & Jones (1998), give fluences a factor of 5–10 lower.

Dust production is estimated using the comet total magnitude and an empirical formula for the correlation between visual magnitude and the water production rate (Jorda, Crovisier & Green 2008). The dust production is then calculated by assuming that all gas production is water, and that the dust to gas ratio is 1. Given that the comet shows significant activity at 7 au, this is not likely to represent the full picture of dust emission by this comet, but

Table 1. Results using the IMEX test model.

r_d H^a	r_d (au)^b	Flux (m^{-2} d^{-1})^c	$N_{\mathrm{MarsExpress}}$^{d}	N_{impact} (m^{-2})^e
H/4	2.4×10^{-03}	5	1.8	0.68
H/5	1.9×10^{-03}	9	2.4	0.90
H/10	9.7×10^{-04}	20	3.1	1.2
H/20	4.8×10^{-04}	23	3.4	1.2
H/40	2.4×10^{-04}	35	3.3	1.2

[a]Radius in au of the box where the density is computed.
[b]Radius in au of the box where the density is computed.
[c]Flux of particles >60 µm.
[d]Number of impacts on the *Mars Express* spacecraft >60 µm.
[e]Number of impact for a 1 m^2 surface area.

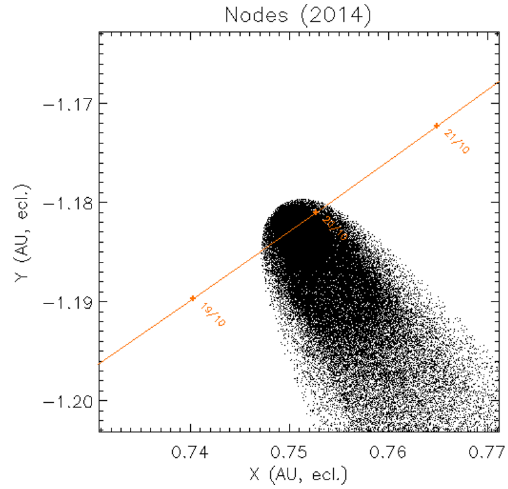

Figure 2. Circumstance of the encounter between Mars and the meteoroids ejected by comet C/2013 A1. The line symbolizes Mars' orbit in the heliocentric J2000 ecliptic reference frame. Units are au. All particles are represented here by black dots. A meteor 'hurricane' is expected from this encounter on October 19.

we assume that the water-driven production inwards of 3–4 au will dominate the dust density at Mars. The total magnitude used is 5.2 and the magnitude slope parameter is 11 (both from the JPL Small Body Database). We use the mass distribution model derived for Comet Halley by Divine & Newburn (1987), as used for comet 67P/Churyumov–Gerasimenko by Agarwal, Müller & Grün (2007). This is a broken power law with a mass distribution index $r = 1.3$ for small particles ($\lesssim 3$ µm) and $r = 2.5$ for larger particles. We use a maximum liftable mass defined by equating the gravitational and gas drag forces on an ejected particle at the comet surface. We assume dust production is a function of the cosine of the zenith angle. The dynamics of the emitted particles are dictated only by solar gravity and radiation pressure only: no additional non-gravitational perturbations are included.

The density is calculated by counting the number of particles within a sphere around *Mars Express*, with the radius of the sphere being a fraction of the stream height. We use radii equal to 1/40 to 1/4 of the stream height (2.4×10^{-4}–2.4×10^{-3} au) to calculate the fluence of particles of size greater than 60 µm on to *Mars Express*, which we take to have a surface area of 2.7 m^2. The resulting fluence on to the spacecraft is roughly stable at ~2–3 particles (Table 1) over the duration of the encounter. This stability assures us there is no significant error caused by the choice of the sphere in which the density is calculated.

4 DESCRIPTION OF THE VAUBAILLON METHOD

The second approach is based on the Vaubaillon et al. (2005a) model, and we recall here the main steps. A large number of simulations mimics the ejection and evolution of dust grain from the comet nucleus as well as their orbital evolution in the Solar system, under gravitational and non-gravitational forces (Burns, Lamy & Soter 1979). The simulations are stopped when the comet is the closest to planet Mars (T = 245 6950.262 12 TDB corresponding to 10/19/2014 18:17:27 – the minimum distance is 15 127 km). The simulated particle size distribution is considered flat in the logarithm scale. One million particles are simulated per size bin, between 10^{-8} and 10^{-1} m in radius, making a total of 7×10^6 simulated particles. Particles larger than 1 µm are simulated, but the density is computed only for particles larger than 100 µm (corresponding to potentially hazardous particles for spacecrafts). A statistical weight is set on each simulated particle based on the real number of particles emitted from the nucleus, computed from the measurement of the [$Af\rho$] parameter (see Section 2). The following physical parameters are chosen, following Vaubaillon et al. (2005a): dust grain Bond albedo: 0.3; Comet nucleus absolute magnitude (from JPL HORIZONS estimates): 10.4; size distribution index: 3.5 (see also Section 5.3).

The spatial density of particles is then computed in a spherical box of a given size d. The size is chosen so that it contains a number of simulated particles greater than 10^3, in order to make sure that the density we compute makes physical sense. Because the density of particles depends on the size of the box, d is changed until the computed density in the considered area is constant. In practice, we look for a maximum of the density value, as a function of d. The ephemerides of the *Mars Express* spacecraft are used in order to compute the relative velocity with the particles. The density of particles is computed in a region centred on the spacecraft. It is noteworthy to say that we also performed the computation at Mars, without seeing any major change in the results. The spacecraft surface area is taken as 2.7 m^2. The total number of particles encountered by the spacecraft is computed for *Mars Express*, as well as for a hypothetical one square metre surface area for reference and comparison purposes (fluence). The results for the different [$Af\rho$] solutions as well as the size distribution are compared to each others'. Considering the relative velocity vector, we derive an equivalent *ZHR*, following Koschack & Rendtel (1990).

5 RESULTS

5.1 Circumstances of the encounter between Mars, *Mars Express* and comet C/2013 A1

Fig. 2 shows the meteoroid stream as well as the comet tail with respect to the orbit of planet Mars, at the time of the encounter. This figure is similar to Vaubaillon et al. (2005a). It is worth mentioning that we have also simulated the meteoroids ejected before the perihelion passage of 2014, but they are not contributing significantly to the picture drawn here. From this figure, we expect a strong meteor storm at Mars on 2014 October, centred around 19:59 (Earth UT), lasting approximately 5 h. Note that this time is not the time of the closest approach between the planet and the comet. Given that the dust is freshly ejected the difference does not come from planetary perturbation, as in the case of usual showers (Vaubaillon, Lamy & Jorda 2006). The time of maximum of a meteor shower

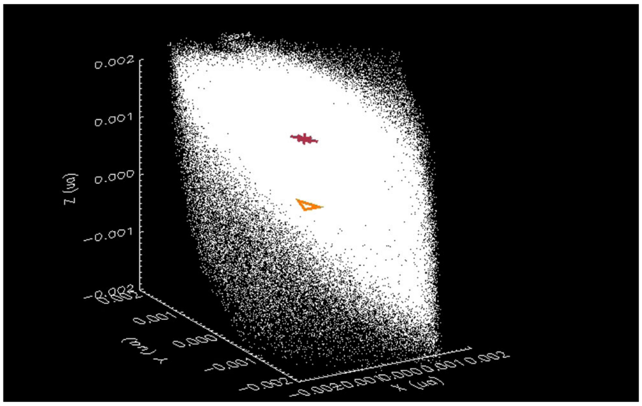

Figure 3. 3D view of the *Mars Express* space probe (triangle) in the meteoroid stream (white dots) ejected by comet C/2013 A1 (red cross) in 2014 October. The spacecraft is clearly in the middle of the stream. The reference frame is centred on the spacecraft and the axis are oriented in the spacecraft–comet relative velocity vector. Units are au.

can be viewed as a projection of the comet trail (or tail) on the planet orbital plane, and depends on the inclination (here 129°.02). The time of closest approach can thus slightly differ with the time of closest encounter, as is the case here.

Fig. 3 shows the *Mars Express* probe with respect to the comet, in a spacecraft-centred reference frame, with axis oriented along the relative velocity vector (see figure for more details). The spacecraft is clearly inside the meteoroid stream, regardless of the size of the particles. Danger of collision is therefore non negligible and detailed results are provided in the following section.

5.2 Space density and fluence

The space density of particles around the *Mars Express* spacecraft, according to our model is presented in Table 2 and Fig. 4 for the Vaubaillon model. The relative velocity between the spacecraft and the particles is found to be 57.42 km s^{-1}.

Our results suggest that a spacecraft like *Mars Express* will experience almost 10 impacts from particles larger than 100 µm in size, which is a very high value. The reason is the extremely high value of the [$Af\rho$] parameter, already measured beyond 6 au. The observed behaviour is similar to comet Hale–Bopp, which was an exceptionally bright comet (Weiler et al. 2003). It is worth mentioning that the low ejection velocity at high heliocentric distance makes the [$Af\rho$] parameter appear extremely high (Jorda, personal communication). Indeed, particles tend to accumulate longer in the vicinity of the nucleus in such a case. The number of impact per square metre is found to be 3.4, which is one order of magnitude larger than what is found by Moorhead et al. (2014). However, substituting $m^{\star} = 10$–9 kg, density = 1 g cc^{-1}, and size distribution index $k = 3.5$ into Moorhead et al. (2014) yields a fluence of five particles per square metre. The fluences given by this detailed model, the simple method (Section 3) and that derived by Moorhead et al. (2014) agree within an order of magnitude, giving us confidence that these high flux rates at Mars are accurate. The real influence of the [$Af\rho$] parameter requires further investigation.

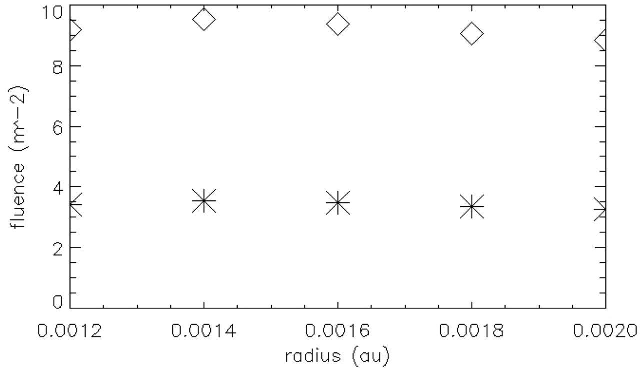

Figure 4. Fluence of meteoroids ejected by comet C/2013 A1 at *Mars Express* (diamonds) and for a normalized surface of 1 m^2 (stars), corresponding to the nominal solution.

5.3 Influence of the [$Af\rho$] parameter and the size distribution

The results above correspond to a size distribution index $s = 3.5$ (which is a usual value for comets) and the 'nominal' [$Af\rho$] solution (see Section 2.2). The influence of the [$Af\rho$] parameter and the size distribution index are showed in Figs 5 and 6. We can see that the [$Af\rho$] parameter introduces a variation of at most one order of magnitude in the results. However the 'high solution' is probably far from reality.

Similarly, changing the size distribution index s introduces a variation of one order of magnitude to the results as well. It is worth mentioning that in this study, s is considered constant over the whole size range, which might not be true, as already pointed out by Vaubaillon & Reach (2010). A low value of s means that the comet produces a large proportion of large particles. When the

Table 2. Results using the Vaubaillon et al. (2005a) model.

r_d (au)[a]	N_{sim}[b]	Vol (au^3)[c]	Density (km^{-3})[d]	Freq (s^{-1})[e]	Tspent (s)[f]	$N_{MarsExpress}$[g]	N_{impact} (m^{-2})[h]
1.200e−03	269 365	7.238e−09	9.462e−02	6.816e+02	6.269e+03	9.197e+00	3.406e+00
1.400e−03	371 621	1.149e−08	8.417e−02	7.662e+02	7.314e+03	9.545e+00	3.535e+00
1.600e−03	461 404	1.716e−08	7.236e−02	8.913e+02	8.358e+03	9.378e+00	3.473e+00
1.800e−03	542 205	2.443e−08	6.223e−02	1.036e+03	9.403e+03	9.074e+00	3.361e+00
2.000e−03	617 991	3.351e−08	5.459e−02	1.182e+03	1.045e+04	8.843e+00	3.275e+00

[a]radius in au of the box where the density is computed.
[b]Number of simulated particles in the box.
[c]Volume of the box.
[d]Space density of particles.
[e]Frequency of impact, given the relative velocity.
[f]Average time spent in the box.
[g]Number of impacts on the *Mars Express* spacecraft.
[h]Number of impact for a 1 m^2 surface area.

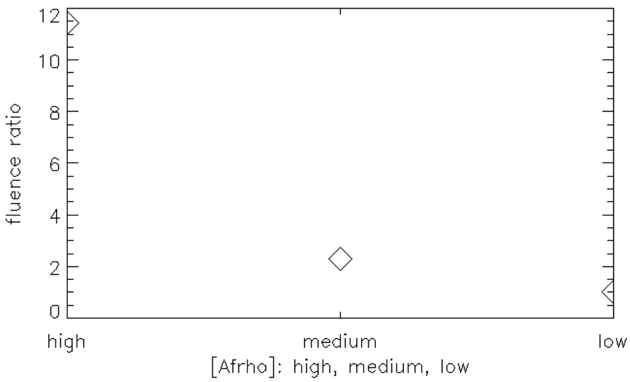

Figure 5. Influence of [$Af\rho$] parameter. The Y-axis is normalized to the fluence obtained with the 'low solution'.

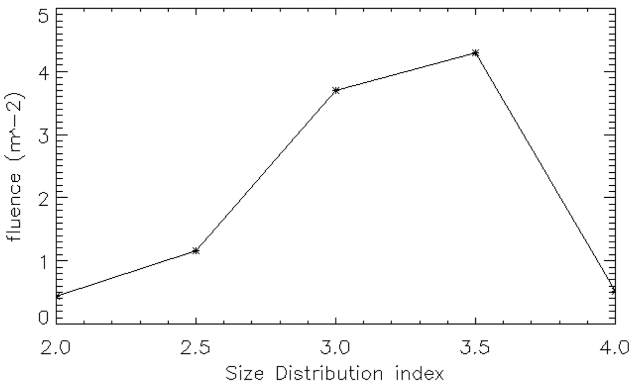

Figure 6. Influence of the differential size distribution index.

size distribution index increases, the proportion of small particles increases, causing the fluence to increase as well. However, there is a limit beyond which micro-sized particles dominates, so that the fluence for particles larger than 100 µm decreases. The size distribution index that maximizes the fluence happens to be 3.5. Keeping in mind the influence of those two parameters, we can say that our results are accurate to about an order of magnitude.

5.4 Influence of the orbit of the comet

As mentioned in Section 2.1, no non-gravitational force can be derived from the observations of the comet at the time this paper is written. Uncertainties in the orbit of the comet cause a variation in the distance of the close encounter of 26 × 10^3 km (138 000–164 000 km). This minimum distance interval includes the difference between our work and the results provided by the JPL HORIZONS solution. This difference is explained by the statistical weight set to each observation [see also Maquet et al. (2012) for further details]. Even assuming high non-gravitational parameters ($A_i \simeq 10^{-8}$), the distance of close encounter is very similar (134 000–169 000 km). Given the size of the box where the density of particles is computed (see Tables 1 and 2) the influence of the uncertainty in the comet orbital parameters is neglected here.

5.5 Meteor Hurricane at Mars on 2014 October 19

We now compute the circumstances of the meteor shower at Mars. The usual altitude of disintegration of the meteoroids in the Martian atmosphere is similar to Earth (≃100 km) (Adolfsson, Gustafson & Murray 1996; McAuliffe 2006). In this section, we compute an equivalent *ZHR* (Koschack & Rendtel 1990), corresponding to the number of meteors a hypothetical human observer located at the Martian surface would see per hour, in perfect sky conditions. Such condition may never happen because of the difference of sky brightness and transparency, but we perform the computation nevertheless for two reasons. The first is to provide a comparison with known meteor showers on Earth, in order give us insight into the relative strength of the phenomenon. Secondly, we want to make the most of such a unique event and derive physical quantities that may assist in the observation of the meteors in the Martian atmosphere, from the ground or space, at Earth or Mars. In particular, in reference to the dubious detection of Martian meteors (Selsis et al. 2005; Domokos et al. 2007), this might be the best opportunity to witness a meteor storm in the Martian atmosphere. Observations by Mars rovers or orbiters, as well as remote detection from the Earth (from the ground or in orbit) will most likely be possible, depending on the geometric circumstances, number and luminous intensity of events.

The radiant of the meteors, computed from the relative velocity measured the simulations, is found to be $\alpha = 32\overset{\circ}{.}38$ and $\delta = -30\overset{\circ}{.}30$, not too far from the ν star of the Fornax constellation. The relative velocity between the comet and the spacecraft as derived from the simulation as 57.42 km s^{-1}. Note that the relative velocity between the comet and Mars does not differ from this value, because the orbital velocity exceeds the dust ejection velocity by several orders of magnitude. From the fluence, we derive the *ZHR* of the meteor shower using:

$$ZHR = f \frac{d}{V} \frac{A}{c} \simeq 4.75 \times 10^9\, h^{-1}, \tag{5}$$

with

(i) f: fluence (3.535 m^{-2})
(ii) V: relative velocity (57.42 × 10^3 m s^{-1})
(iii) d: radius of the considered area (1.4 au = 4.2 × 10^8 m)
(iv) A: atmosphere area covered by a naked eye (37 200 km^2), from Koschack & Rendtel (1990)
(v) $c = 13.63$: correction factor (no unit), taking $s = 3.5$, corresponding to $r = 2.3$, from Koschack & Rendtel (1990) and Vaubaillon et al. (2005a).

Note that using the fluence derived by Moorhead et al. (2014) of 0.15, we compute *ZHR* $\simeq$ 1.95 × $10^8\, h^{-1}$, which is one order of magnitude less than our estimate, but still five orders of magnitude higher than any meteor storm ever observed on Earth using modern techniques (we recall that during the 2001 Leonids earth the measured *ZHR* was close to 3000 h^{-1}). Although other spectacular meteor showers have been witnessed, even the 1966 Leonids at Earth (*ZHR* $\simeq 10^6\, h^{-1}$) was still two to three orders of magnitude lower than what will happen at Mars in 2014 (Jenniskens 2002; Vaubaillon, Colas & Jorda 2005b).

6 CONCLUSION

A meteor shower of this strength has never been forecast before. As such, we describe this event as a 'meteor hurricane', defined as a meteor shower exceeding $10^6\, h^{-1}$. If the photometry measurements of the comet are confirmed and match the [$Af\rho$] solutions given in this paper, the danger to spacecraft around Mars on the 2014 October 19 is real and should not be ignored. Space agencies are called to take all precautions to protect their spacecraft and spacecraft subsystems. However, such an encounter is also of high scientific interest because of the unique opportunity to observe not only the first 'meteor hurricane' ever witnessed, but also the deposit of cometary material into the thin Martian atmosphere. We therefore call planetary scientists to make everything possible to observe this extraordinary event.

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